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Diurnal root zone temperature variations affect strawberry water relations, growth, and fruit quality

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A B S T R A C T

To test the hypothesis that the effect of daily root zone temperature (RZT) variations would affect strawberry plant performance, root systems of Control 'Albion' strawberry plants Treatment 1 (T1) were maintained at 20 °C (no stress), while plants in other treatments were exposed to different diurnal temperature swings about the daily mean of 20 °C. In treatment 2 (T2), temperature swing was 5 °C (mild) which had a total variation of 10 °C (Tvar-10) with a minimum of 15 °C and maximum of 25 °C, treatment 3 (T3) had a variation about the mean of 10 °C (moderate) with a total variation of 20 °C (Tvar-20) with a minimum of 10 °C and maximum of 30 °C, or 15 °C (severe) swings about the mean in treatment 4 (T4) with a diurnal total variation of 30 °C (Tvar-30) with a minimum of 5 °C and maximum of 35 °C. Leaf area and shoot dry weight of plants in the severe treatment were 30% lower than Controls. Root dry weight in the severe treatment was 30% lower than in the mild treatment. Fruits in the moderate and severe treatments were 22% smaller than in the mild treatment. Fruit soluble sugar content was elevated slightly by RZT fluctuation. Shoot concentrations of N, Mg, Fe, B, Zn were not affected by RZT, but there were small differences in concentrations of P, K, Ca, Mn, and Cu. Nutrient uptake of N and Ca were not affected, but P, K and Mg were about 35% less in Tvar-20 and Tvar-30. RZT variation had no effect on chlorophyll content or number of leaves, maximum carboxylation rate, photosynthetic electron transport rate, maximum CO_2 assimilation rate, or fluorescence parameters (F_v/F_m and ϕPSII). There was little effect of RZT on predawn or midday stem water potential (SWP), but the SWP was substantially lowered in the severe treatment at mid-morning when RZT was about 5 °C and air vapor pressure deficit was at its daily maximum. We attributed the reduced shoot and root growth to the transient reduction in SWP when RZT was near 5 °C. Overall, the consequences of diurnal RZT fluctuations for strawberry production appear to be small if the minimum temperature is above 7 °C.

1. Introduction

Recent interest in the commercial open-field production of strawberries in soilless substrates has provoked concern about possible effects of root zone temperature (RZT) fluctuations on fruit yields and quality. Physical characteristics of substrates affect both the degree and rate of RZT fluctuation. For example, the high organic matter content and low bulk density of most soilless substrates result in a low apparent heat capacity, and the inter-particle water film pathways through their coarse pores lead to high heat conductivity (Schaetzel and Anderson, 2005). Therefore, in contrast with mineral soils, in which daily temperature fluctuations at 10 cm depth are usually small, ~5 °C when ambient temperatures range from 9 to 28 °C (Pregitzer and King, 2005), soilless substrates at 10 cm depth can undergo large daily temperature fluctuations that follow air temperature fairly closely, ~15 °C when ambient temperatures range from 17 to 34 °C (Personal data, Davis CA July 2011).

Survival and root growth of container-grown plants in outdoor systems can be negatively affected by extremely high and low root zone temperatures (Miralles et al., 2009). RZT has a marked effect on plant productivity of many species (Pregitzer and King, 2005), and it may have a greater effect on growth than air temperature (Korner and Paulsen, 2004; Xu and Huang, 2000). It affects root metabolism,

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growth and morphology, impacting critical root functions such as nutrient uptake and water absorption (Dong et al., 2001; Hussain and Maqsood, 2011; Pregitzer and King, 2005). Rates of root respiration and oxygen consumption typically double with each 10 °C increase in RZT (Pregitzer and King, 2005; Morad and Silvestre, 1996), while the solubility of oxygen is inversely related to temperature (Marfa et al., 2005). As RZT increases, the combination of increased root oxygen demand and decreased oxygen concentration in soil water can result in hypoxic conditions that impair root growth (Chapin, 1974; Barr and Pellet, 1972).

Exposure of plants to low root zone temperature causes a decline in stomatal conductance (g_s), which has been attributed to reduced root permeability to water that leads to decreased plant water status (Anderson and McNaughton, 1973; McWilliam et al., 1982). Net photosynthesis (A_N) can be negatively affected by low RZT as g_s declines (Ahn et al., 1999).

Extreme RZT fluctuations could affect strawberry fruit quality and yield. Fruit quality depends on the interaction of several factors (e.g., sugar content, acidity and aroma profile) that may be influenced by RZT. For example, a high RZT may result in a decreased leaf area and reduced photosynthesis, limiting carbohydrate availability to fruits (Carlen et al., 2007; Cordenunsi et al., 2002). Water stress associated with high or low RZT (Lee et al., 2005; Graves and Aiello, 1997) may result in smaller fruit with lower sugar concentrations (Liu et al., 2007). Plant stress associated with extreme RZT could stimulate ethylene production and increase the synthesis of alcohol-acyltransferase, a rate-limiting step for biosynthesis of aromatic esters in strawberry (Defilippi et al., 2005).

Negative responses to constant high or low root zone temperatures have been found in strawberry plants (Bar-Yosef, 2008; Geater et al., 1997; Biela et al., 1999; MacKenzie and Chandler, 2009) and other crops (Pritchard et al., 1990; Urrestarazu et al., 2003; Bar-Yosef, 2008; Kafkafi, 2008). However, plant responses to diurnal fluctuations in RZT have not been reported. The present study was undertaken to test the hypothesis that the magnitude of daily RZT fluctuations would affect strawberry plant growth, nutrient uptake, gas exchange, water relations, yield, and fruit quality of strawberry.

2. Materials and methods

2.1. Plant material and experimental set up

The experiment was conducted in a greenhouse at the Environmental Horticulture research facilities at the University of California, Davis, CA between 5 October 2012 and 15 February 2013. Frozen strawberry (*Fragaria x ananassa* 'Albion') propagules were obtained from Lassen Canyon Nursery (Yuba City, California); upon receipt the plants were thawed and the roots trimmed to 10 cm length. Plants with similar crown diameter and root system volume were used in the experiment. Each plant was immediately placed in a solution culture container that was 19 cm on a side and 22 cm deep. Plants were held above the nutrient solution by a piece of Styrofoam perforated according to the plant crown diameter and set snug on the container lid. A nutrient solution (Table 1) was circulated through plastic tubing to each container, and air was bubbled continuously in each container to maintain an average dissolved oxygen concentration of 9.9 ± 3.5 mg L^{-1}.

The root zone temperature of each container was independently managed using a digital temperature controller (Temperature Controller II E54, Micromatic, Sparks, NV). Two closed-loop coils of 1 cm diameter ThermaPEX heat transfer polyethylene tubing (PexSupply LK PEX, Sweden) were placed in each container, one for circulation of hot water (for instances where the temperature needed to be raised) and the other for chilled water (for times when the temperature required to be lowered). Water was circulated through the coils from reservoirs of chilled and hot water that were maintained at −4 °C and 45 °C, respectively. In the chilled water system, salt water (5 M $CaCl_2$) was chilled using a chest freezer (Model FGCH2OM7LW, Frigidaire, Augusta, GA. Hot water was held in an insulated reservoir in which the temperature was maintained with three electrical heating elements (742 G, Marshalltown Company, Marshalltown, IA). The water in each of these systems was isolated from the nutrient solution and the root zones of the plants.

Table 1
Nutrient solution composition for 'Albion'strawberry plants grown in stirred solution culture for 19 weeks. The nutrient solution electrical conductivity was 1 dS m^{-1}. The pH was maintained between 5.8 to 6.2 by addition of 1 M potassium carbonate or 1 M sulfuric acid, as needed.

Cations		Anions	
Nutrient	Concentration mg L^{-1}	Nutrient	Concentration mg L^{-1}
K	58.5	NO_3—N	63
Ca	80	P	15.48
Mg	18.2	S	32.64
Fe	2.8	B	0.6
Mn	0.4	Mo	0.03
Zn	0.2		
Cu	0.1		

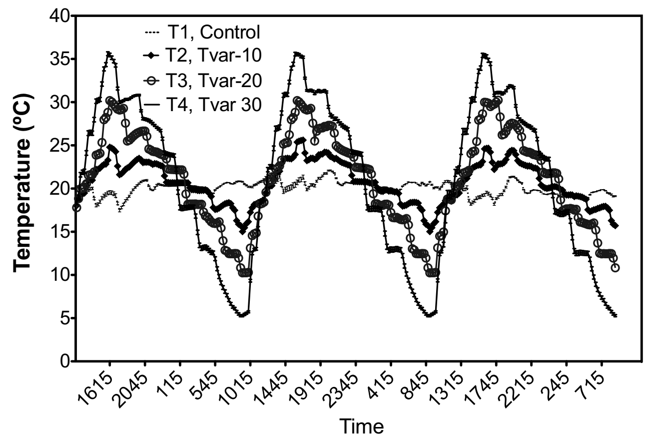

Fig. 1. Three day sample of four different daily root zone temperature fluctuation regimes of constant 20 °C (control, T1), 15–25 °C (Tvar-10, T2), 10–30 °C (Tvar-20, T3) and 5–35 °C (Tvar-30, T4), as a function of time on 'Albion' strawberries plants grown in solution culture in 2-gallon pots for 19 weeks.

Four treatments were imposed, each providing a mean RZT of 20 °C. Control plants of T1 were kept at a constant 20 °C RZT. In the T2 treatment, a diurnal 10 °C RZT fluctuation (Tvar-10), ± 5 °C about the 20 °C mean was created by gradually decreasing RZT during the night and early morning to a 15 °C minimum at about 10:00 am, then gradually increasing RZT to a 25 °C maximum at about 4:00 pm The T3 and T4 treatments were managed in a similar fashion to achieve RZT fluctuations of 20 °C and 30 °C, Tvar-20 and Tvar-30 respectively. There were five replicates per treatment, arranged in a completely randomized design. All the plants in any one treatment were interconnected with tubing so that the temperature of the solution entering any one container was always near the set-point temperature of that treatment.

2.2. Environmental measurements

RZT was monitored, continuously averaged, and recorded (Fig. 1) using T-type duplex insulated thermocouples (Omega Engineering, Stamford, CT) set at a depth of 10 cm in the nutrient solution of each pot and attached to a micro logger (CRX23, Campbell Scientific Inc., North Logan, UT).